Journal of Manufacturing Processes 30 (2017) 1–13

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro

Technical Paper

Simultaneous improvement of mechanical strength, ductility and corrosion resistance of stir cast Al7075-2% SiC micro- and nanocomposites by friction stir processing

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ARTICLE INFO

Article history:
Received 21 March 2017
Received in revised form 30 August 2017
Accepted 5 September 2017

Keywords:
Age-hardenable alloy
Stir casting
Nanocomposite
Grain refinement
Friction stir processing
Electron microscopy

ABSTRACT

Present work investigates the mechanisms of simultaneous improvement of tensile properties, wear properties and corrosion resistance of stir cast Al7075–2 wt.% SiC micro- and nanocomposites through microstructural refinement by friction stir processing (FSP). Optical, scanning and transmission electron microscopy were used to investigate the microstructural evolution. After the FSP, the nanoparticles reinforced composite showed better mechanical properties than that of the microparticles reinforced composite. Tensile strength (>3 times) and wear resistance were found to increase significantly with simultaneous enhancement of the ductility (10 times). The improvement is ascribed to the grain size reduction, distribution of SiC nanoparticles uniformly within the matrix, increase particle-matrix interface characteristics and elimination of casting defects such as porosity after the FSP. The corrosion potentials of the as-cast composites were found to shift towards noble direction after the FSP. Enhancement of corrosion resistance after the FSP is attributed to the decrease in the heterogeneity on the surface and uniform dispersion of the reinforced particles, which reduced the effective active surface area exposed to the corrosive solution. All such beneficial effects were found to be superior for the nanoparticles reinforced composite due to the improved particle/matrix interface characteristics and dispersion strengthening.

1. Introduction

Aluminum (Al) alloys are mostly used in structural, aerospace, military and automobile sectors due to their excellent specific strength, high stiffness and outstanding corrosion resistant [1]. The major problems existing in Al based alloys are: they possess very low wear resistance and a moderate level of mechanical strength. Several techniques, such as alloying, age-hardening and particulate reinforcement have been evolved to enhance the mechanical strength of these alloys. Among these, particulate reinforcement is found to be the most suitable route to improve the wear resistance, mechanical strength and corrosion resistance of the Al alloys [2–4]. Therefore, aluminum matrix composites (AMCs) could be used as potential structural materials to substitute conventional monolithic Al alloys. Moreover, the AMCs have low thermal expansion coefficient and high specific strength, which are very important for structural applications. AMCs can be reinforced with a large number of ceramic materials, e.g.; Al_2O_3, SiC, TiC, B_4C and MgO etc. Among the various reinforcements, silicon carbide (SiC) is particularly attractive due to its high wear resistance, elastic modulus, good resistance to oxidation, excellent mechanical properties at high temperature and low cost [5]. Furthermore, SiC generally does not react with the matrix material and does not create undesirable phases. Various processing methods, such as stir casting, compo casting, ultrasonic casting, squeeze casting, powder metallurgy etc. have been developed to manufacture AMCs [6–9]. Among the variety of processing routes, the stir casting is the most commonly used technique due to its flexibility, low processing cost, better matrix-particle mixing, near-net shape fabrication of the composites and high production rate [10]. Mahendra et al. [11] fabricated AMCs reinforced with fly ash particles by stir casting route and stated a high hardness, high compression & tensile strength and better impact toughness with the increase in reinforcement percentage. Bhushan et al. [6] reinforced 10 and 15 wt.% SiC particles (20–40 μm) in 7075 Al matrix by stir casting process and reported that distribution of SiC particles was excellent in AA7075. Micron size ceramic particles reinforced in Al and most of its alloys enhanced the tensile strength of the matrix, but on sacrificing its

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http://dx.doi.org/10.1016/j.jmapro.2017.09.005
1526-6125/

ductility [7,12]. However, use of nanosize reinforcement strengthens the matrix while retaining its good ductility [13–15]. For example, Zhang et al. [13] investigated tensile properties of Al2014-SiCp (~40 nm) composites at elevated temperature and reported that SiC nanoparticle reinforcement in Al2014 alloy improved the tensile strength of the matrix remarkably without sacrificing its ductility. However, it is challenging to disperse nanosize particles uniformly within the matrix by most of the production methods. It is due to the fact that the nanosize particles have large surface area-to-volume ratio thereby higher tendency towards agglomeration and poor wettability in most metallic melts [2,16]. Several approaches such as rolling [17], forging, friction stir processing (FSP) [8], ECAP [18], hot extrusion [19] were applied to improve dispersion of reinforcement and to remove various casting defects. Some researchers found that the above-mentioned secondary processes were useful to modify the microstructural constituents and thereby enhance the mechanical properties of the composites. Amongst the several aforementioned metal working processes, the FSP has been established as a standard technique for microstructural modification and material processing [20–23].

The FSP technique was originally proposed by Mishra et al. [24,25] using same fundamentals as friction stir welding. It uses extreme plastic deformation and frictional force to mix the metal and refine the microstructures thereby removing inherent casting defects (porosity, particle clustering and agglomeration of particles). These microstructural changes significantly enhance the mechanical properties (ductility, tensile strength and hardness) and wear resistance [22,26,27]. Bauri et al. [20] investigated the influence of FSP on microstructural characteristics and thereby improved various mechanical properties, such as tensile strength/yield strength (UTS/YS) and ductility of Al–5 wt.% TiC composite. They found that the FSP could effectively homogenize the particles distribution in the composites. Besides the distribution of particles uniformly, the FSP leads to refine the grain structure. Thus, the mechanical properties of the cast composites could be enhanced significantly. Kurtyka et al. [28] used the FSP to enhance the mechanical properties of A339 + 10% SiC cast composite. They reported a substantial improvement in SiC particle distribution and enhancement of mechanical properties in comparison to the starting sample. Recently, the effect of the FSP on modification of microstructures and mechanical characteristics of AA7075-TiB_2 in-situ composite has been reported in [22]. Initially, particles of TiB_2 were clustered and segregated along the grain boundaries. After the FSP, distribution and morphology of the TiB_2 particles were changed significantly and thereby enhanced the tribological and mechanical properties of the composite. Hoziefa et al. [8] demonstrated that casting followed by FSP was a promising route to develop Al based nanocomposite. An Al2024 alloy based composite containing 1 wt.% of Al_2O_3 nanoparticles (50 nm) was fabricated by compocasting method followed by FSP. They found that the FSP of the composite improved the yield and tensile strength, respectively, by 30 and 71% in comparison to that of the as-cast composite. This is attributed to the distribution of Al_2O_3 nanoparticles uniformly and matrix grain size refinement. These results indicate that the FSP is an effective method to modify the microstructure and thus improve mechanical properties of cast AMCs.

However in a single study, stir casting of Al alloy reinforced with micron- and nanosize particles followed by FSP to modify the microstructures has not been investigated yet. Therefore, in this work, attempts have been made to develop Al7075–2 wt.% SiC micro- (size 20–60 μm) and nanocomposites[1] (size 30–80 nm) using stir casting technique followed by FSP. Aim of the FSP is to modify the cast microstructure thereby enhancing its mechanical strength, ductility, wear resistance and corrosion resistance simultaneously for its practical applicability.

2. Material and experimental procedure

Micron size SiC powder (Alfa Acer, average size 20–60 μm) was ball milled in a tungsten carbide grinding media using a planetary mill Pulverisette 6 (Fritsch) for 25 h to produce nanosize SiC particles (30–80 nm). The rotation speed of the mill was set at 300 rpm and the ball to powder mass ratio was kept at 15:1. As a process control agent, toluene was poured in the vial before milling. Subsequently, after the milling, size of the SiC particles was examined by transmission electron microscope (TEM). The TEM sample was prepared first by dispersion of small amount of ball milled powder ultrasonically in methanol and then a drop of the dispersed liquid was drop cast on to the carbon coated copper grid of 3 mm diameter using a micro-pipette and allowed to dry up. After that, the sample with carbon coated copper grid was placed within the TEM for the analysis.

Al based composites were produced in a bottom pouring stir casting machine. The experimental set-up used in the production of the composites was already shown in our previous work [29]. For each casting, an argon gas controlled resistance heating electric furnace was used to melt one kg of Al7075 alloy. Before charging the furnace, a coating of high-temperature paste (wolfrakote) suitable up to 1000 °C was applied to the inside wall of the furnace and on the stirrer to avoid any contamination and to avert sticking of molten material. After holding the melt at 750 °C for 30 min, 2 wt.% of SiC particles were incorporated in the melt at a feeding speed of 4 g/min. To improve wettability and to remove moisture problem, the SiC powder was preheated for 2 h at 800 °C before pouring into the molten metal. After SiC addition, mechanical stirring was carried out at 600 rpm for 10 min to achieve a distribution of the particles uniformly. Finally, the composite melt was bottom-poured in a vacuum steel mold which was also preheated to 300 °C. The cast composites were allowed to solidify in the mold at room temperature. Throughout the casting process, an argon atmosphere was maintained completely to avoid any oxidation problem. During fabrication of both micro- and nanocomposites, same experimental setup was used and the castings were produced under same conditions. The cast ingots of both micro- and nanocomposites were sliced into pieces of dimension 60 mm × 45 mm × 6 mm. A specially designed FSP tool with cylindrical pin (length = 4 mm & diameter = 6 mm) and concave shoulder (diameter = 25 mm) was used for the FSP. As the FSP parameters have great influences to produce defect-free fine recrystallized microstructure and thereby final mechanical properties of the processed samples. FSP parameters (rotational speed, traverse speed and geometry of tool) were optimized to obtain defect-free processed samples. For this purpose, several numbers of trials have been carried out with the different combination of rotational speeds (720 and 1025 rpm) and traverse speeds (25, 50 and 100 mm/min). The defect-free processed region with uniform SiC particles distribution and refined microstructure was achieved only at 1025 rpm and 25 mm/min traverse speed. The detail of process parameters optimization is given in Table 1S as a supplementary material. The FSP was conducted at room temperature without using any coolant. The FSP conditions were kept same for both micro- and nanocomposites for comparisons.

Microscopic investigation of the as-cast and friction stir processed (FSPed) composites was carried out using an optical microscopy (Leica DMI 5000 M), scanning electron microscopy (FEI-Quanta 200FE-SEM) and TEM (FEI Technai 20 G2S-Twin TEM). Transverse sections of the FSPed (nugget) zone were taken

[1] Hence onwards, it will be called as MC and NC, respectively.